X-615-63-36

N64 11794 *

CODE-1

NASA TMX 51251) OTS:

14 p.

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OTS PRICE

XEROX $ 1.60 ph

MICROFILM $ 0.80 mf.

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[1963] 14 p ref Submitted for publication

6021307

GODDARD SPACE FLIGHT CENTER

GREENBELT, MD.

*Defence Research Telecommunications Establishment

R9T-10377

PRELIMINARY RESULTS FROM THE VLF RECEIVER
ABOARD CANADA'S ALOUETTE SATELLITE*

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On September 29, 1962, the Alouette satellite was launched into orbit and, although designed primarily as a topside sounder,[1] a broad band VLF receiver was included in the payload. Since operation of the VLF experiment is incompatible with the other experiments in the satellite only a limited schedule of VLF observations is carried out at the present time. This includes 4-6 minutes of observation once per day, when the vehicle is within telemetry range of Ottawa, 3 or 4 recordings per week at either Prince Albert or Resolute Bay, and 2 recordings per week at Quito, Ecuador. Once per week these observing periods are arranged in conjunction with recordings at additional telemetry stations to give consecutive observations at Resolute, Ottawa, Quito, Ecuador, Antofagasta, Chile and South Atlantic, so the VLF spectrum is observed continuously as the satellite moves through its full range in latitude. Although the analysis of the results of this program are far from complete, it has revealed some interesting features of whistlers and ionospheric noise as seen in the ionosphere. In addition some comparisons of simultaneous observations of the VLF band, from the ground and in the satellite, have been made. These preliminary observations form the substance of this note.

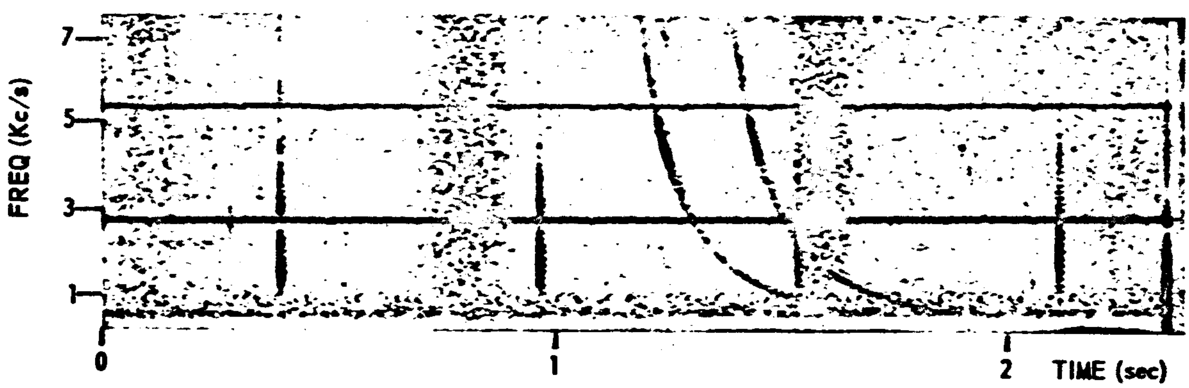
Before presenting any results, some features of the satellite orbit and the receiver characteristics will be noted. The satellite moves in a nearly circular orbit at a height of 1000 km and has an inclination of about 80 degrees to the

*To be published in Nature — In Press

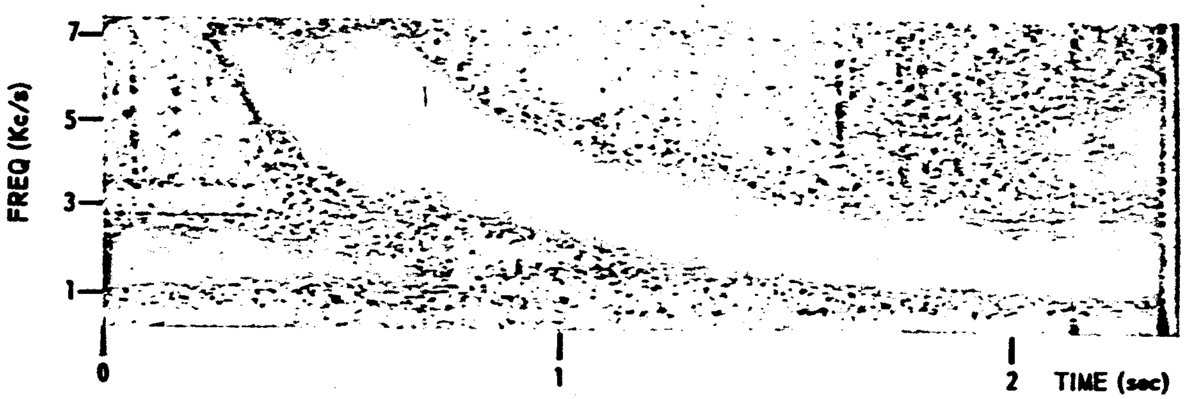
equator. This allows observation of the VLF spectrum over a very wide range in latitude while the circular orbit simplifies the interpretation of the results. The receiver covers the VLF band from 600-10,000 cps., and has an AVC circuit with a time constant of .2 sec. which holds the receiver output constant to within 3 db for variations in the amplitude of the input signal of up to 80 db. The ionospheric sounder and the VLF receiver are both connected to the same 150 ft. dipole antenna. A matching network, permanently connected across this antenna, optimizes the sounder performance and attenuates the VLF signal by about 50 db. The maximum gain of the receiver is 85 db.

Vanguard III has already observed whistlers within the ionosphere[2], but because of the small inclination of this satellite's orbit the recordings made were all for relatively low latitudes. The published observations showed whistlers of rather pure tones much like those shown in Fig. 1a which were observed by Alouette at a latitude of 1.7°S. Thus our data is in accord with previous satellite observations. There are, however, marked differences between the low latitude and high latitude whistlers observed by Alouette. Whistlers observed in the ionosphere near Ottawa are generally of the form shown in Fig. 1b. Such "swishy" whistlers are quite commonly observed on the ground in the vicinity of Ottawa but it was usually considered that their diffuse character was due to propagation of electromagnetic energy from the southern to the northern hemisphere via several lines of force of the earth's magnetic field. Those waves then emerged from the ionosphere at several locations and propagated to a ground receiver via the waveguide mode. A whistler such as that shown in Fig. 1b requires a modification of this view. Also visible in Fig. 1a are two dark straight lines at frequencies of 2.8 and 5.6 kc's. These are due to the DC to DC converters of the satellite power supply and are found on most of the satellite records.

Fig. 2 shows two whistlers which were observed at about 10°N latitude. The surprising feature of these records is that while the whistlers are relatively



(Fig. 1a) LAT. 1.7°S. LONG 65.6°W. NOV. 28, 1900.07 UT



(Fig. 1b) LAT. 37.4° N. LONG. 83.9° W. DEC. 11, 0703:02 UT

Fig. 1 **Comparison of whistlers observed by the Alouette satellite at a high and low latitude.**

intense, they extend over a limited frequency band. Moreover the two whistlers are found in different parts of the frequency spectrum, although their measured dispersions indicate that they originated in similar latitudes. A possible explanation of this observation is that at low latitudes the different frequency components of a whistler sometimes follow slightly different paths through the

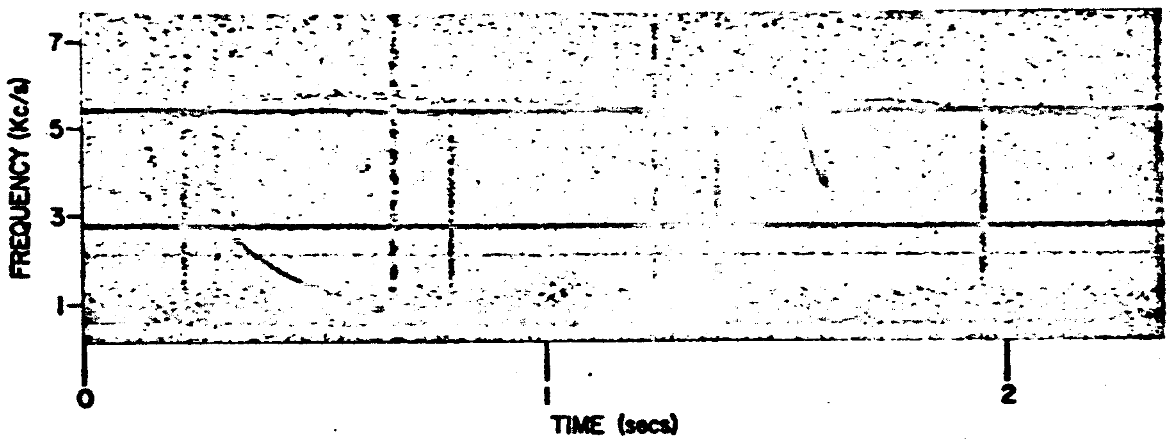


Fig. 2 Whistlers of limited bandwidth observed at a low latitude.

ionosphere. Simultaneous ground and satellite observations of whistlers such as those of Fig. 2 should provide a test of this suggestion.

Fig. 3 shows a comparison of a whistler as observed by the satellite and by a ground station. At the time of these recordings the sub-satellite point was long. 69.9°W lat. 35.6°N and the ground station was Ottawa long. 75.4°W lat. 45.2°N. Since timing for these two recordings is accurate only to about 1 sec. the spherics observed on the ground are aligned with the signals observed in the satellite at a frequency of 7.5 Kc/s. This is not strictly correct for even a frequency of 7.5 Kc/s. requires a travel time from the lightning flash to the satellite of the order of 50 ms and lower frequencies require considerably greater travel times. In spite of this, the relative positions of the signals on the two records should be the same and this can be seen to be the case. This record shows that only a small fraction of the spherics recorded on the ground are observed in the satellite. To reach a ground receiver propagation from a lightning flash is via the waveguide mode which has relatively little attenuation, and hence lightning strokes occurring over a large region of the earth's surface are observed by a ground receiver. For a lightning stroke to be observed by

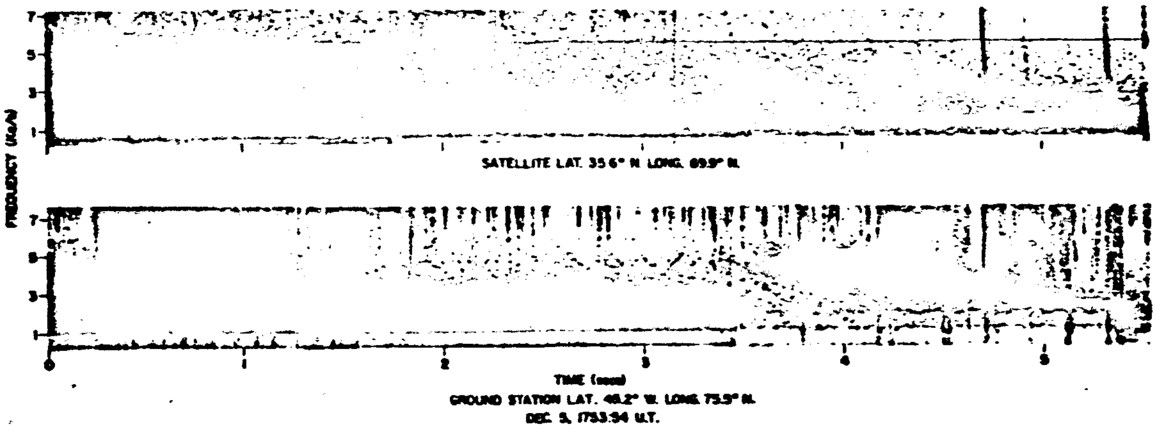


Fig. 3 Comparison of simultaneous records from the VLF receiver in the satellite and the Ottawa ground station. During this interval a diffuse whistler, presumably, associated with the spheric that caused the short fractional-hop whistler seen in the record was observed by both receivers.

the satellite propagation must be via the whistler mode. Because of the high refractive index of this mode, waves whose angles of incidence on the ionosphere vary over a wide range, are refracted so that their wave normals become almost vertical once they are in the ionosphere. As a result energy propagating via this mode can reach the 1000 km level of the satellite only over a restricted region above its point of entry into the ionosphere. Thus it is reasonable to expect that only a small fraction of the spherics observed on the ground correspond to observable signals at the satellite.

Only with satellite borne whistler receivers is it possible to observe signals which have propagated via the whistler mode along a fraction of a whistler path between hemispheres. As yet there is no established nomenclature for describing such signals. In this note, all the signals observed by the satellite which are believed to originate in lightning flashes will be termed fractional-hop whistlers. Those which have propagated directly from the ground to the satellite without crossing the magnetic equator are classified as short fractional-hop whistlers in contrast to those which cross the magnetic equator one or more times and are designated as long fractional-hop whistlers. In Fig. 3 the intense signals shown on the left of the satellite record are short fractional-hop whistlers while the diffuse signal on the right is a long fractional-hop whistler.

On the left hand side of Fig. 3 is a spheric which produced a very strong signal at the satellite. Since the intensity of this signal is much greater than any of the other signals observed in the satellite it is probable that this spheric originated very close to the sub-satellite point. This figure also illustrates a diffuse whistler which was observed on the ground and in the satellite at about the same time. The latitude at which this observation was made, and the time delay between the two-hop whistler and the lightning stroke which produced the intense fractional-hop whistler is consistent with the assumption that the two-hop whistler was produced, at least in part, by this stroke. If this is correct then in the case illustrated some of the energy of the two hop whistler entered and left the ionosphere very close to the same point. It is also of interest to note that the whistler as observed on the ground is similar to that observed in the satellite.

Fig. 4 illustrates another peculiar type of VLF signal observed by the satellite. On this record are two closely spaced short fractional-hop whistlers whose dispersion approximates that expected for a signal propagating directly from a lightning flash to the satellite. Close to these two whistlers are two other signals whose separation in time, to the accuracy with which it can be determined, is equal to the time separation of the preceding short fractional-hop whistlers. The dispersion of these signals is considerably greater, about a factor of 3, than that of the short fractional-hop whistlers but is much too small for a long fractional-hop whistler at the latitude where this record was obtained. It is also interesting that these signals do not extend over as great a frequency range as the short fractional-hop whistlers. If these signals are assumed to originate

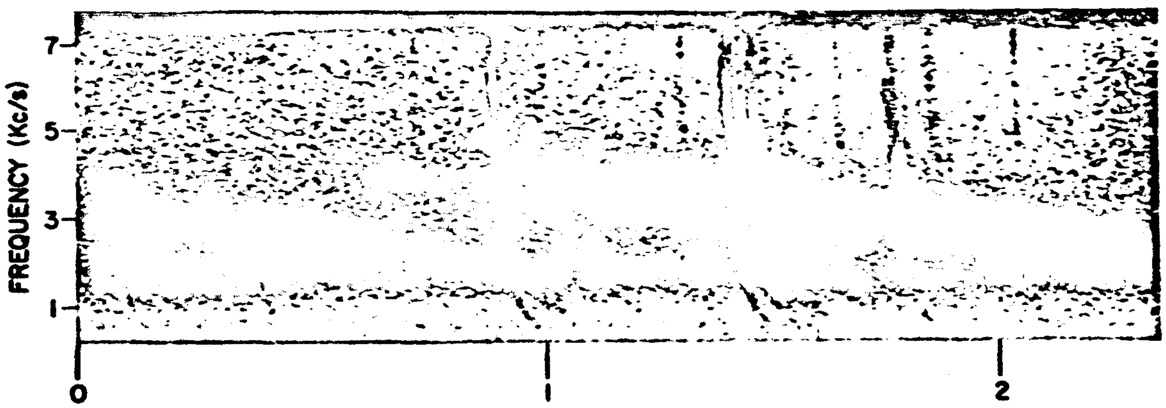


Fig. 4 Short fractional-hop whistlers which appear to be associated with signals that have a dispersion lying between that of short and long fractional-hop whistlers.

in an electromagnetic impulse, and to propagate via the whistler mode, then their time of occurrence coincides with that of the impulse giving rise to the pair of short fractional-hop whistlers. Thus a possible interpretation of this record is that two lightning flashes which occurred at close to the same time, both produced electromagnetic radiation which propagated directly to the satellite via the whistler mode. Some of this energy was partially reflected by an irregularity near the satellite height, returned to the ground where it was reflected and returned to the satellite with considerably greater dispersion than the direct signal.

Another comparison of observations in the satellite and on the ground is given in Fig. 5. Again as in Fig. 3, the spherics were used to align the two records. The ground observations were made during darkness and it can be seen that the majority of the spherics seem to suffer a cut-off at about 1600 cps. This is thought to be due to a cut-off phenomenon associated with the waveguide formed by the earth and the lower edge of the ionosphere in which, particularly at night, spherics propagate to very great distances with little attenuation. On

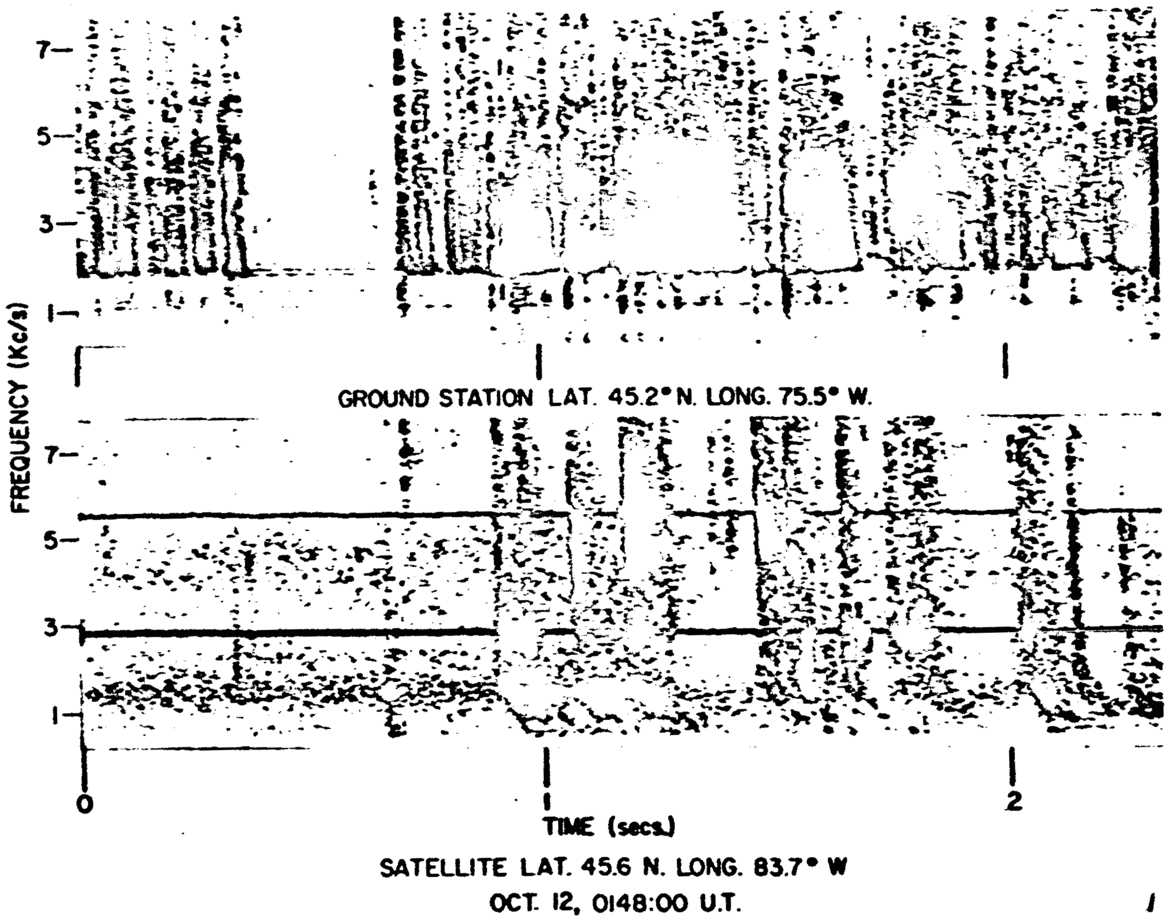


Fig. 5 Simultaneous ground and satellite records which show the association between spherics and short fractional-hop whistlers.

this view the spherics which have clearly discernable components below the cut-off frequency are those which occur relatively close to the receiver. The observations in the satellite confirm this view. At the time of these observations the satellite was almost above the ground receiver, and only those spherics which were observable at frequencies below the cut-off are seen in the satellite. It is also noteworthy that these short fractional-hop whistlers observed in the satellite are rather diffuse. This is probably due to scattering by irregularities in the ionosphere below the satellite. In fact such scattering may be important in understanding the diffuse whistlers illustrated in Figs. 1b and 3.

A very peculiar feature of Alouette observations can be seen in Fig. 2. Here several vertical lines appear, resembling closely the appearance of spherics on a ground based VLF receiver. This record was received, however, in the satellite and any impulsive signal propagating from the ground to the satellite should experience considerable dispersion. Since the straight lines of Fig. 2 give no indication of any dispersion comparable to that of the short fractional-hop whistlers of Fig. 3 and 4, it is concluded that these impulsive signals are not due to propagation of energy from a lightning stroke to the satellite via the whistler mode. Since no other form of propagation of energy from a lightning flash into the ionosphere has been observed, it seems likely that these impulsive signals are due to some source within or near the satellite itself. Examination of many records shows that such lines may be present at almost any latitude; sometimes they are very plentiful (15 - 20 on one sonagraph record) while at other times they are absent. Sometimes they occur at fixed intervals while at other times they occur randomly. At present it is not known if these clicks are due to the satellite instrumentation, to the impact of particles on the antenna or the satellite skin, to discharges in the vicinity of the vehicle, or to some other unknown origin.

In addition to the whistlers of various types which have been illustrated a great variety of ionospheric noise has been observed by the satellite. Examples of some forms of this noise are shown in Fig. 6a and 6b. In these figures the noise is confined to two discrete frequency bands, but in Fig. 6a the noise is continuous whereas in Fig. 6b it is sporadic. Both of these records were made at latitudes for which ionospheric noise is very common. Comparison of noise as observed in the satellite and on the ground indicate that the bandwidth of the noise observed by the satellite is usually less than that observed on the ground. It is also found that the satellite observes much more noise below 1000 cps than is seen on the ground.

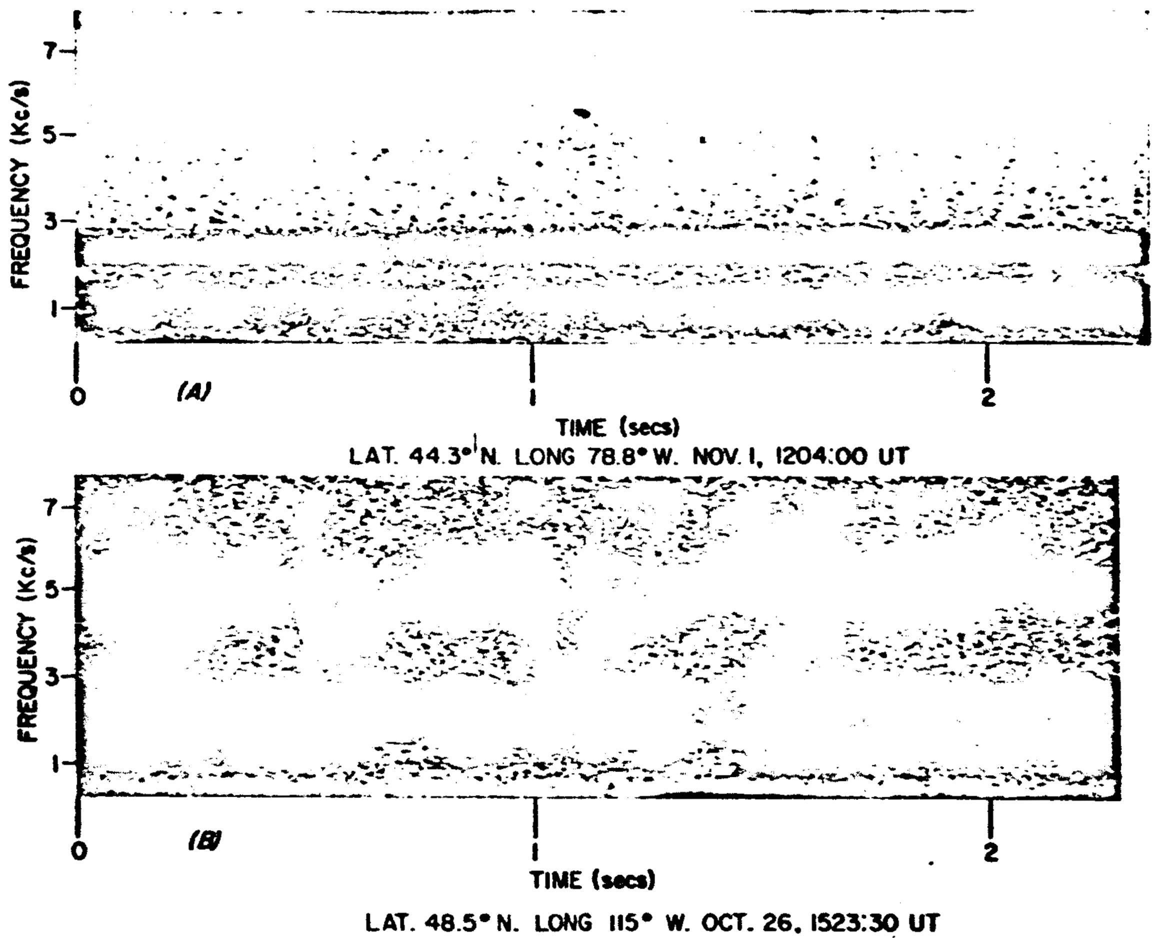


Fig. 6 Two examples of Ionospheric noise observed by the Alouette satellite.

One of the most interesting observations of ionospheric noise is shown in Fig. 2. This record was obtained by the Quito telemetry station when the satellite was at about 10°N latitude. Even at this low latitude a relatively constant band of ionospheric noise is present. The observed lower limit of this noise band is probably set by the cut-off of the VLF receiver. The upper edge of the band lies between 1.1 and 1.3 Kc/s. In addition to this noise, a signal of limited bandwidth and quasi-constant frequency occurs at about the second harmonic of the DC-DC converter frequency. Such signals occur frequently but as yet it is not known if they are due to ionospheric noise or are generated within the satellite itself.

In Fig. 7 three very interesting recordings of ionospheric noise are shown. In example A the noise is sporadic but shows a systematic tendency for the lowest frequency at which noise is found to decrease as the satellite moves from 41.5°N to 48°N. Above 48°N sporadic noise is found throughout the entire frequency range of the VLF receiver with no well defined lower limit. In example B two discrete bands of noise are present, but the frequency limits of these bands increase steadily as the satellite moves from 49°N to 44°N. In example C the noise is of a more continuous nature. Again, however, there is an over-all tendency for the frequency of the lower edge of the noise band to decrease as the satellite moves from 44°N to 49°N. It is also remarkable that this noise band

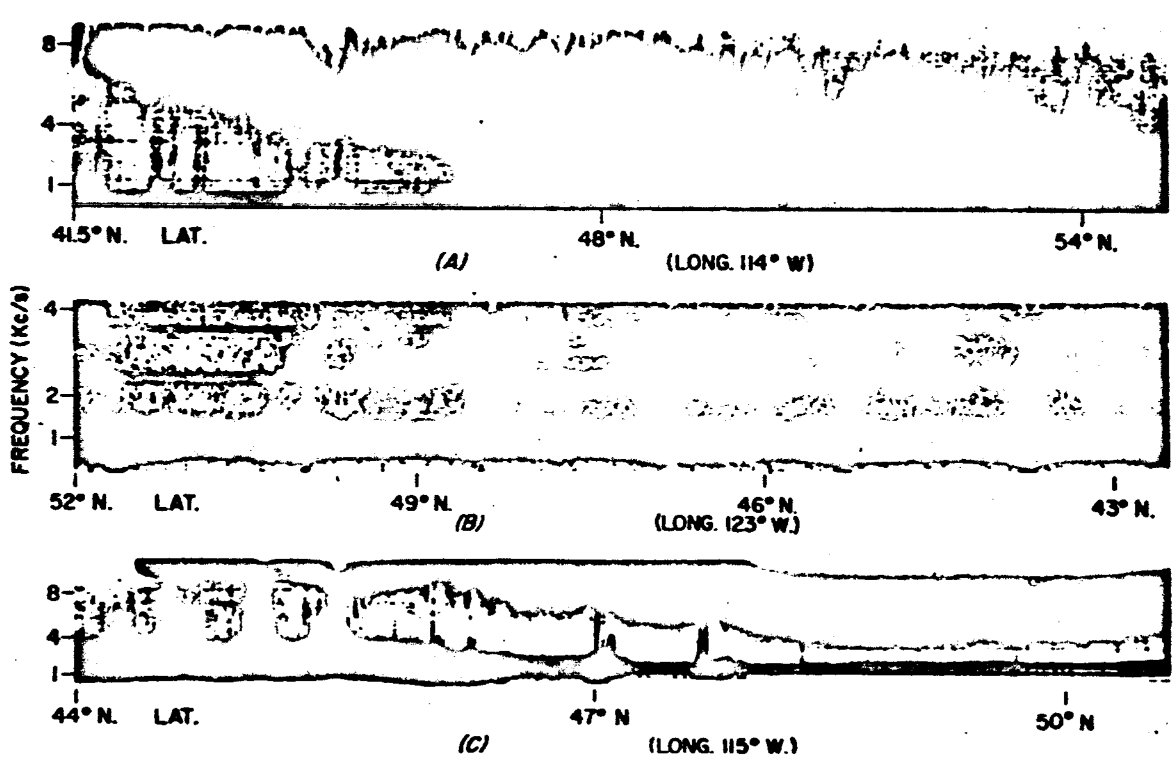


Fig. 7 Three examples of Ionospheric noise which exhibits systematic changes in the spectral distribution of the noise with the satellite latitude. Example A was obtained on Oct. 26, 1962 1521 - 1526 UT. Example B on Nov. 3, 1962 0122 - 0127 UT. Example C was obtained on Dec. 14, 1962 0857 - 0900 UT.

appeared rather suddenly when the satellite was at 44.5°N. These systematic changes are thought to be due to changes with latitude in the mean drift velocity of the particles which generate ionospheric noise.

Such latitude effects will be studied extensively during the satellite passes in which the VLF receiver is continuously in operation. To assist in such studies, and also to aid in the comparison of whistlers as observed in the ionosphere and on the ground, a large network of ground whistler stations make recordings during times when the satellite is in their vicinity and also during the entire sweep of a pole to pole satellite recording. This network of whistler stations consists of: Great Whale River, P.Q.; Suffield, Alberta; Ottawa, Ontario; Schefferville, P.Q.; Dartmouth, New Hampshire; Ontario, New York; Logan, Utah; Green Bank, W. V.; Stanford, California; Santiago, Chile; USNS Eltanin, West Scotia Basin, Antarctica; Byrd Station, Antarctica; Rights Station, Antarctica; and South Pole, Antarctica. Recordings at this extensive network of stations is possible through the co-operation of R.A. Helliwell of the Radio Science Laboratory of Stanford University, and M. G. Morgan of Dartmouth College, New Hampshire.

In conclusion, the high inclination orbit of the Alouette satellite presents the opportunity to study whistlers and VLF emissions over a range of latitudes and is expected to provide new information on the generation and propagation of these waves. Since the relation between VLF propagation and the magnetic lines of force can be directly investigated, more accurate measurements of the variation of whistler dispersion with latitude are possible. This should result in a better determination of the distribution of electrons in the exosphere under normal and magnetically disturbed conditions.

Finally there are events which can be observed in the satellite but not on the ground and these, of course, should receive particular attention. The short fractional-hop whistlers which have been illustrated are one example of such events. The dispersion of these whistlers can be determined with high precision and is related to the total electron and ion content between the ground and the satellite. Since the electron density at and below the satellite is measured independently by ionospheric sounding of the top and bottom of the ionosphere, dispersion measurements of short fractional-hop whistlers should yield information on the heavy ions of the ionosphere and on the manner in which the whistler mode enters the ionosphere.

ACKNOWLEDGMENT

We wish to express our thanks to Mr. W. E. Mather who operated the ground whistler station at Ottawa and made the recordings shown in this paper.